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Title: End-to-End Modeling of a Kilonova

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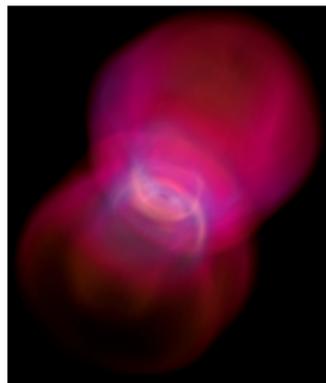
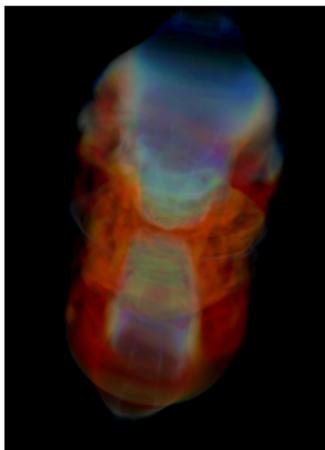
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End-to-End Modeling of a Kilonova

Jonah M. Miller, in collaboration with:
S. De, K. Lund, S. Curtis, T. Sprouse,
N. Wolfe, V. U-Hurtado,
And Many More...

Los Alamos National Laboratory

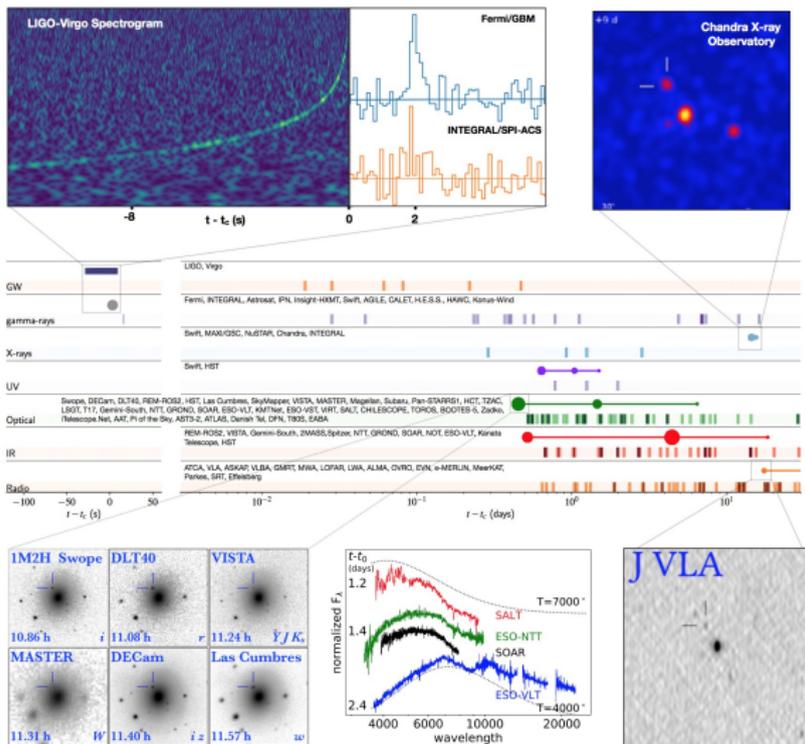
UNAM Gravity Seminar





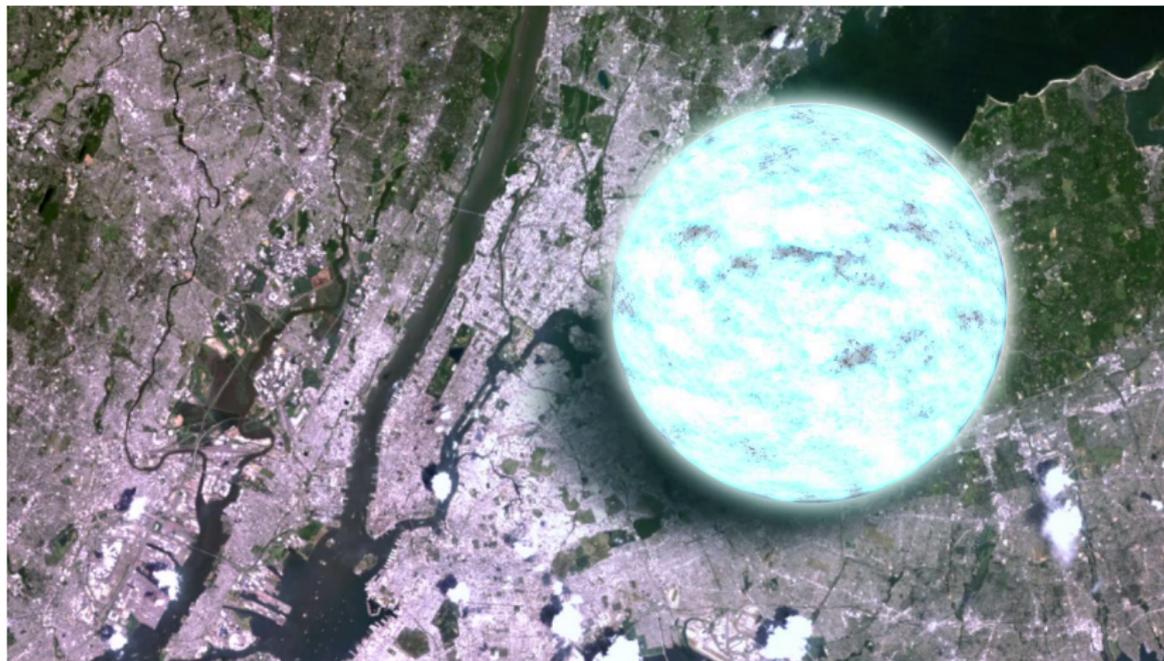
Ashley Mackenzie for Quanta Magazine, March 23, 2017

The 170817 Merger



Abbot+, 2017

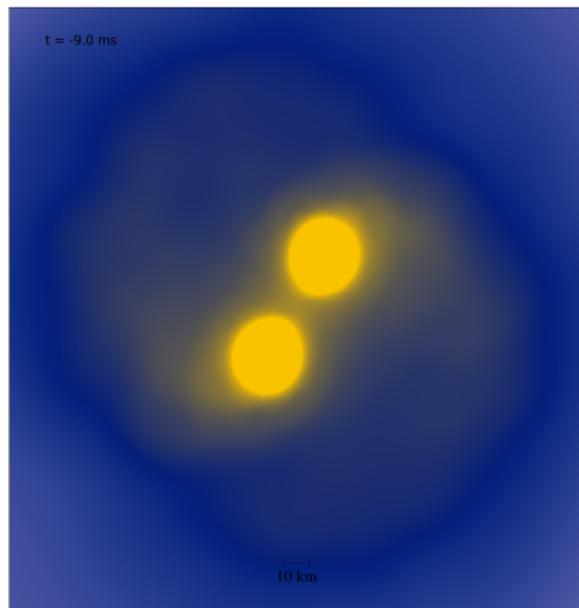
Neutron Stars



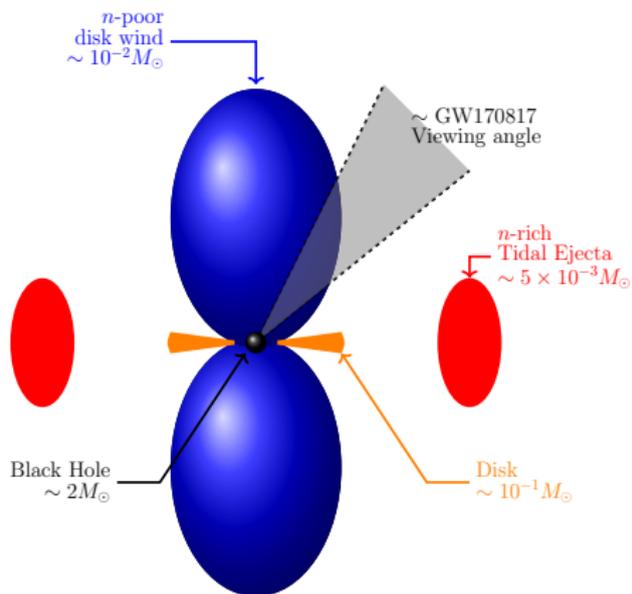
Wikimedia Commons

- An overview of the process of forward modeling, from end to end
 - Emphasis on the disk, and neutrino transport
- A deeper look into a related system, a collapsar disk, and what it tells us about mergers

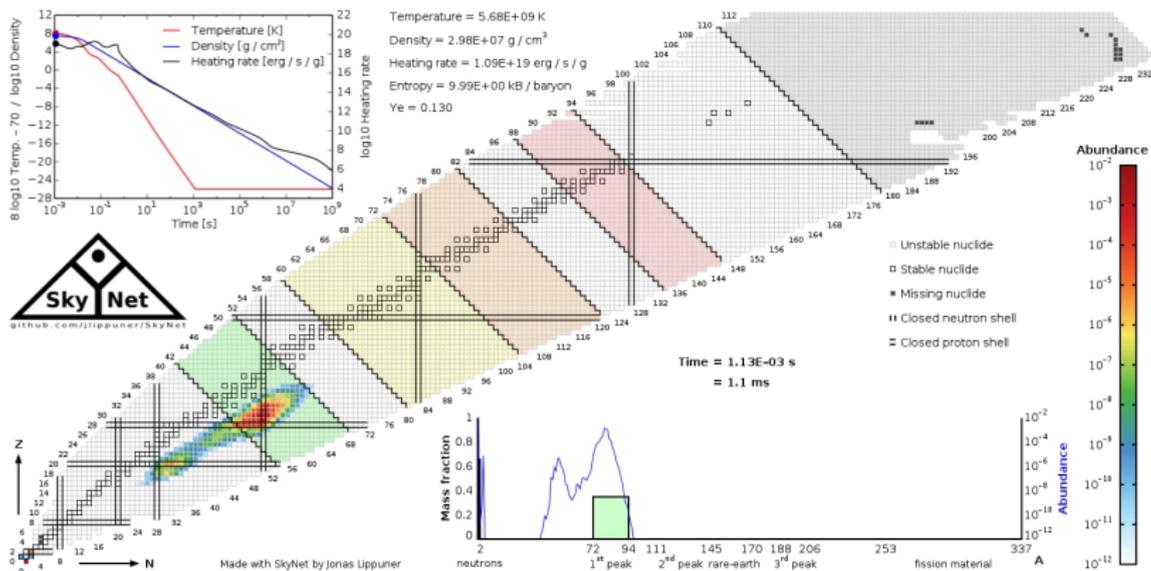
Neutron Star Mergers: A 2+ Component Model



Co-design summer school, 2016

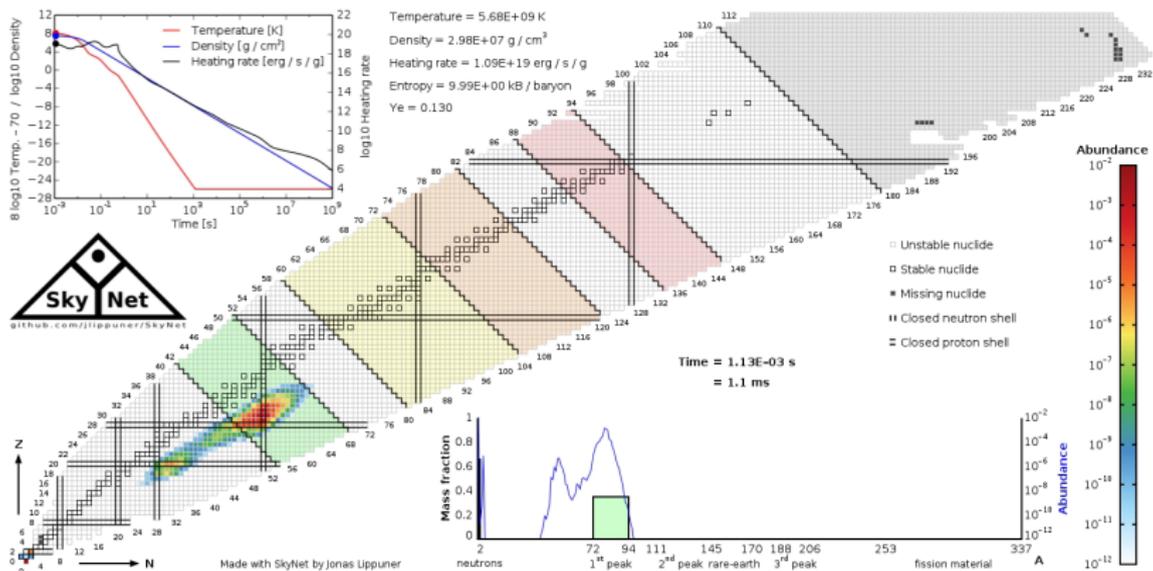


The r-process

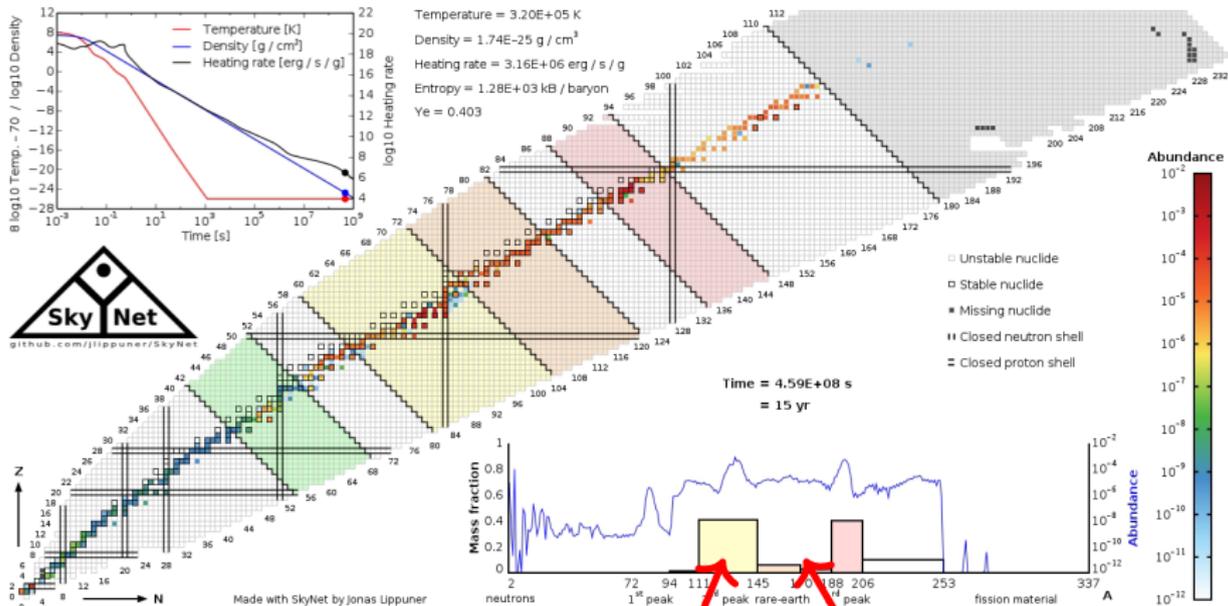


Courtesy of J. Lippuner

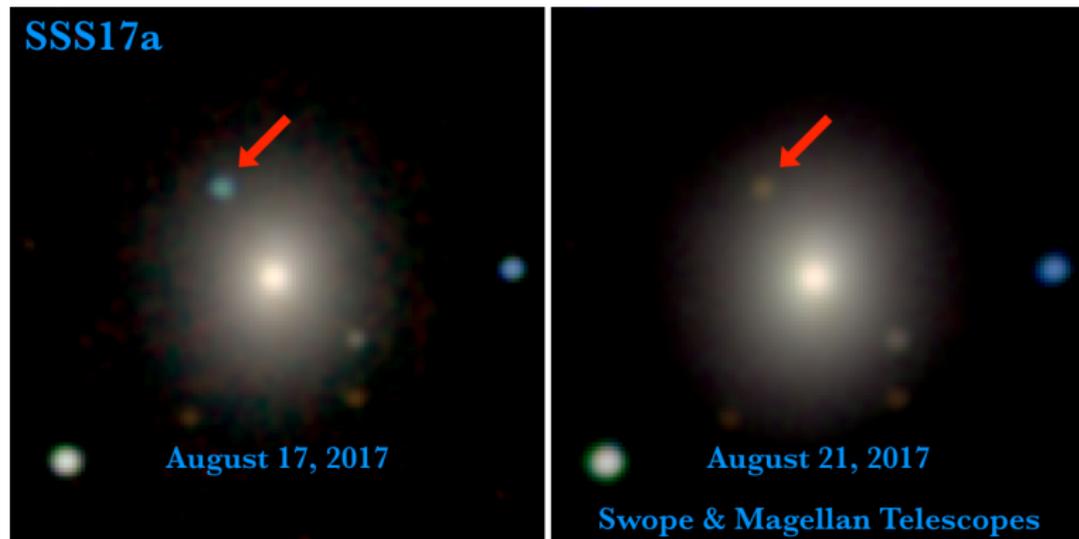
The r-process



Courtesy of J. Lippuner



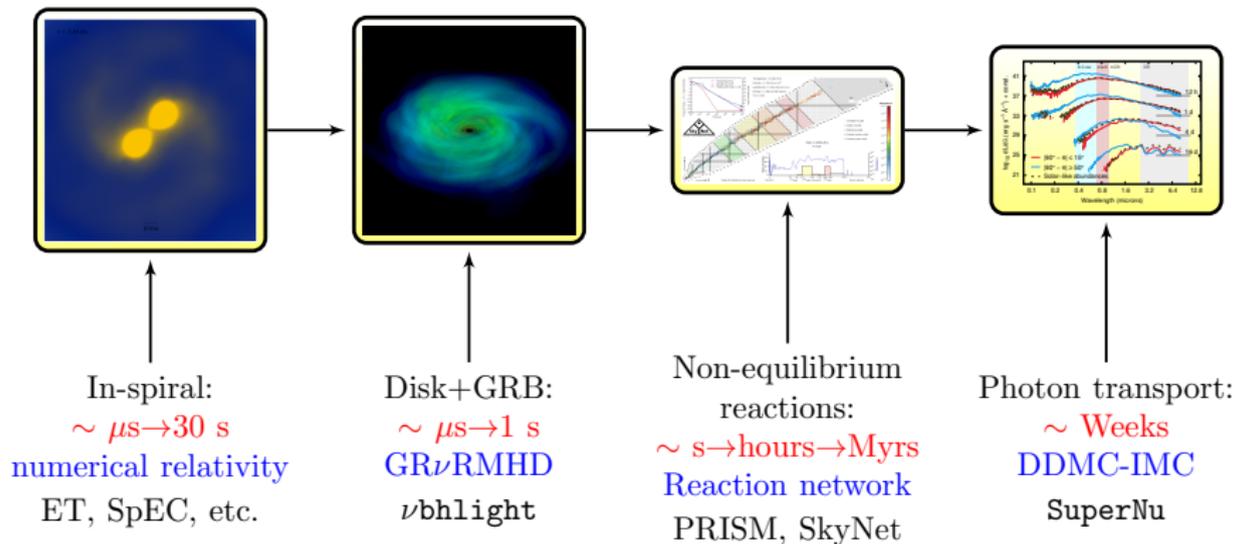
Not opaque ——— Opaque to visible light



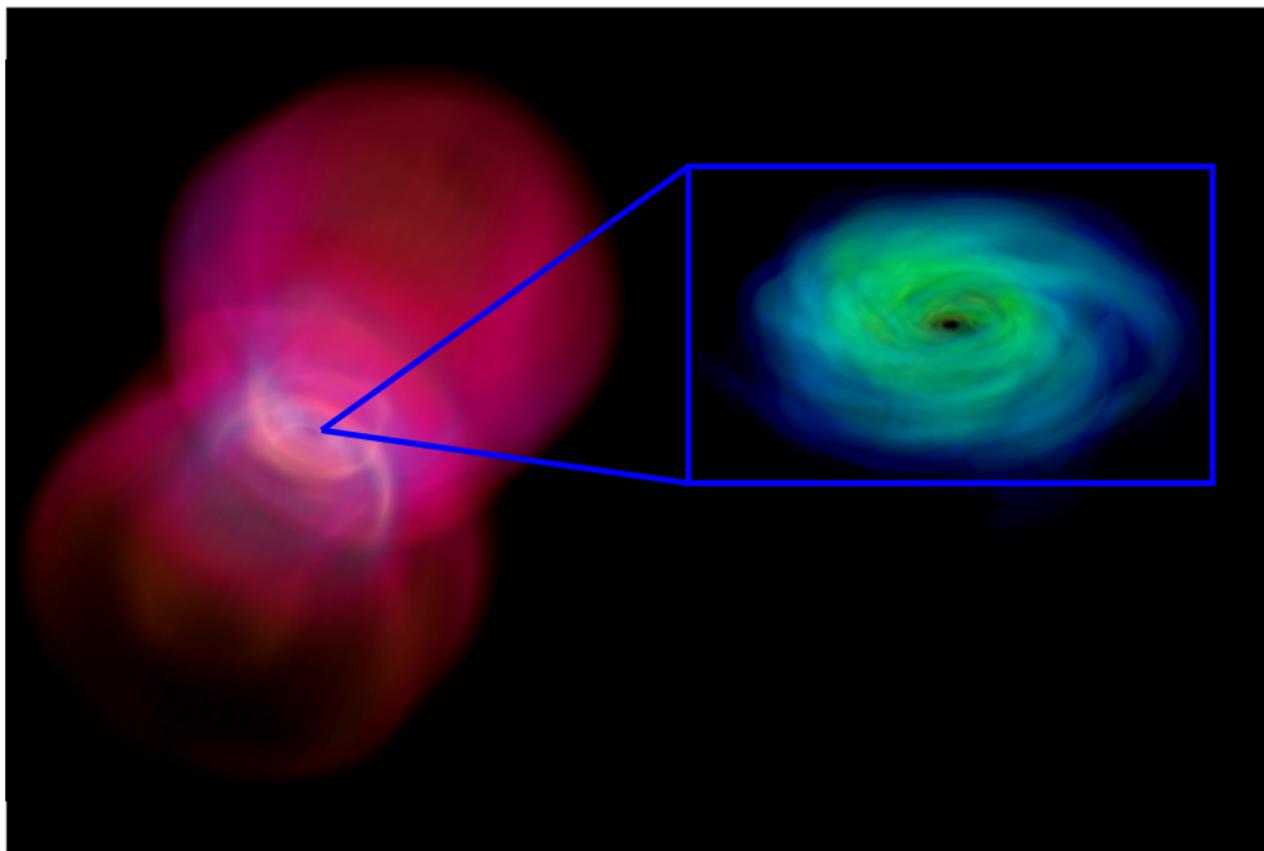
M2H/UC Santa Cruz and Carnegie Observatories/Ryan Foley

The Makings of a Kilonova

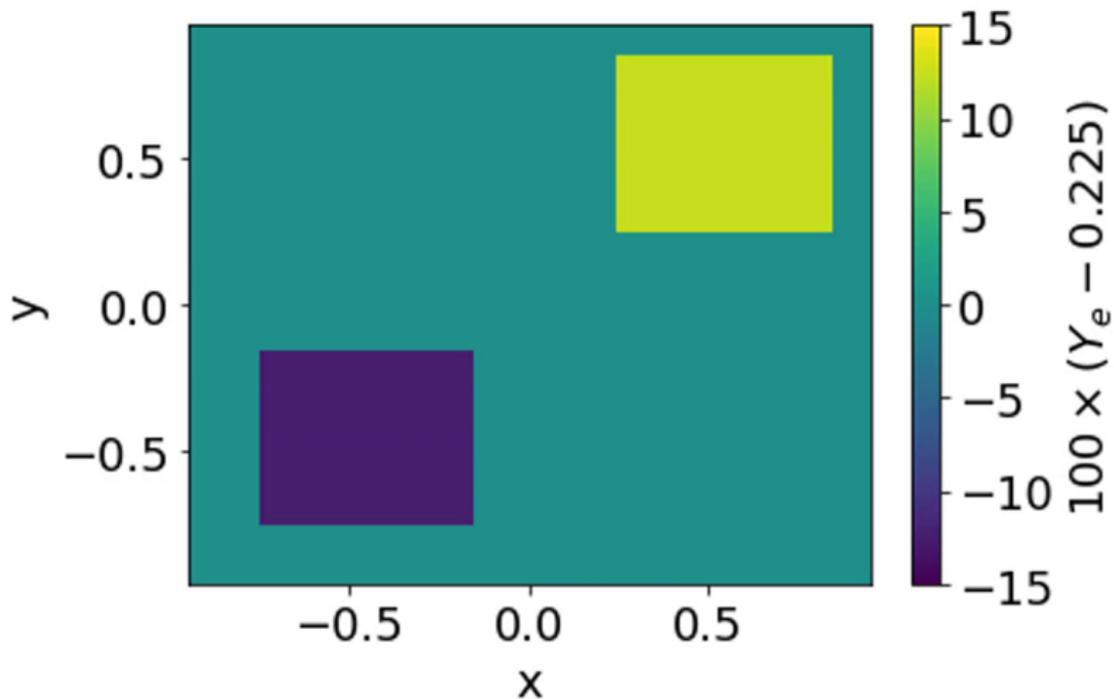
- Duration/relevant time scales
- Methods



Lets Start With the Disk

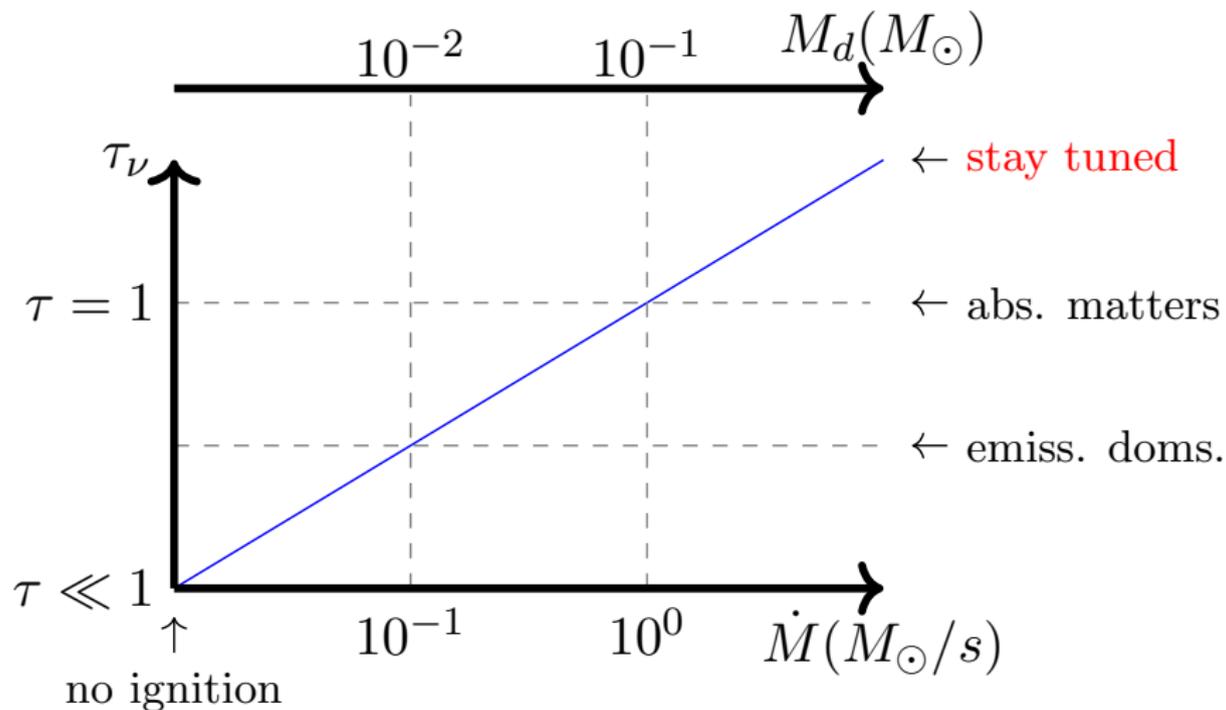


Neutrino Transport Matters!

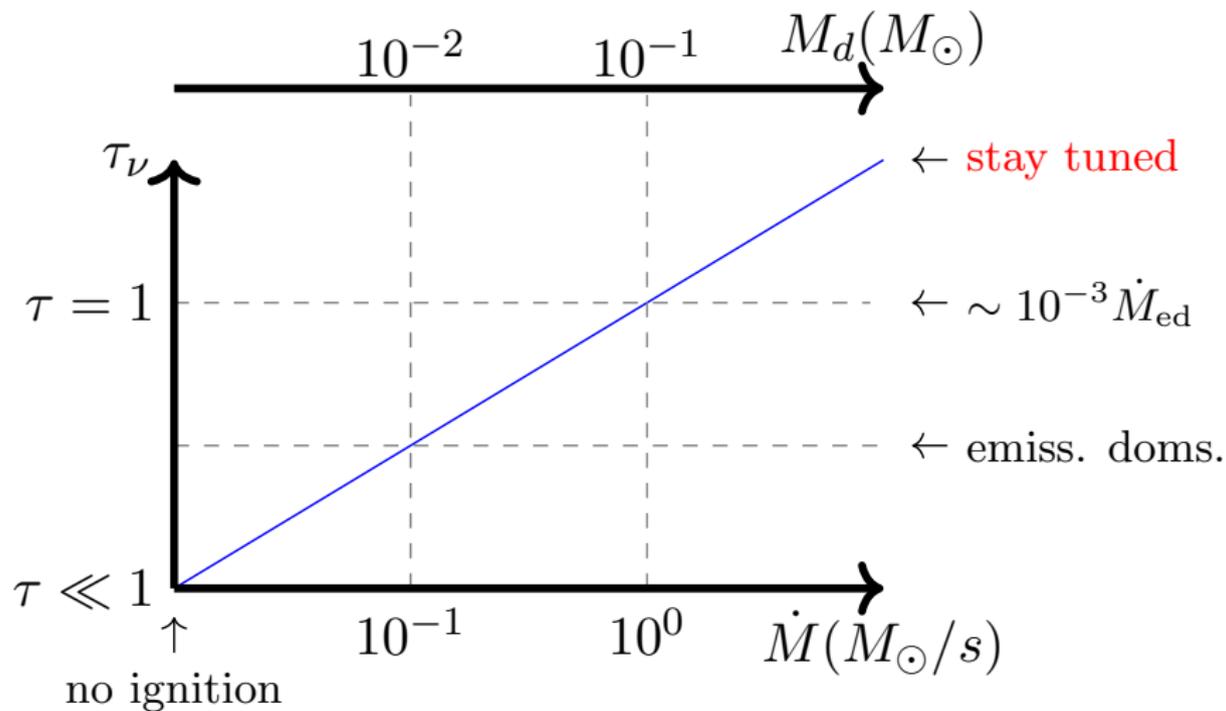


JMM, B. R. Ryan, J. C. Dolence. *ApJS* **241** 30 (2019)

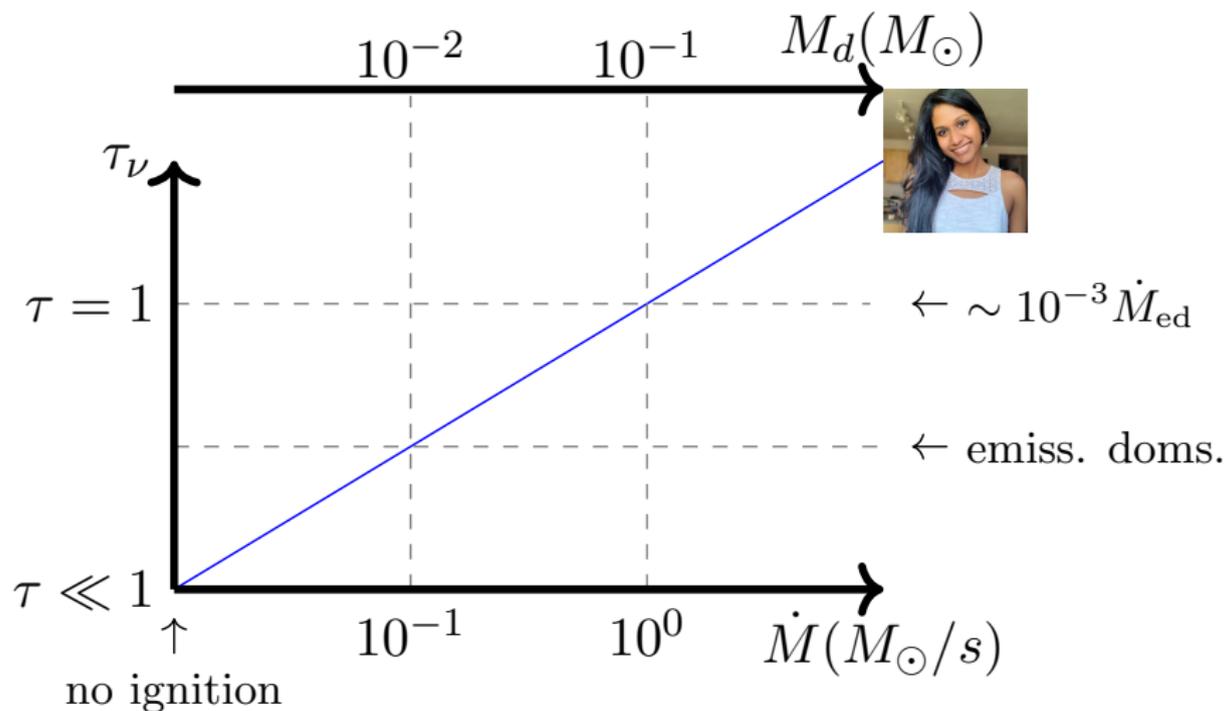
How Much Does Transport Matter?



How Much Does Transport Matter?



How Much Does Transport Matter?



- General relativity
 - Rotating black hole spacetime
- Plasma physics
 - Ideal magnetohydrodynamics
- Nuclear physics
 - Hot gas treated as being in nuclear-statistical equilibrium via **equation of state**
 - Cooling outflow treated in postprocessing via **nuclear reaction networks**
- Radiation physics
 - Material is opaque to photons, can be incorporated in plasma physics
 - Material *not* opaque to **neutrinos**.
 - Neutrinos can *change the composition of the material* by converting neutrons to protons and vice versa.

- Mass conservation:

$$\partial_t (\sqrt{-g} \rho_0 u^t) + \partial_i (\sqrt{-g} \rho_0 u^i) = 0$$

- Momentum and Internal Energy Conservation:

$$\partial_t [\sqrt{-g} (T^t_\nu + \rho_0 u^t \delta^t_\nu)] + \partial_i [\sqrt{-g} (T^i_\nu + \rho_0 u^i \delta^i_\nu)] = \sqrt{-g} (T^\kappa_\lambda \Gamma^\lambda_{\nu\kappa} + G_\nu)$$

- Magnetic Fields

$$\partial_t (\sqrt{-g} B^i) - \partial_j [\sqrt{-g} (b^j u^i - b^i u^j)] = 0$$

- Composition

$$\partial_t (\sqrt{-g} \rho_0 Y_e u^t) + \partial_i (\sqrt{-g} \rho_0 Y_e u^i) = \sqrt{-g} G_{ye}$$

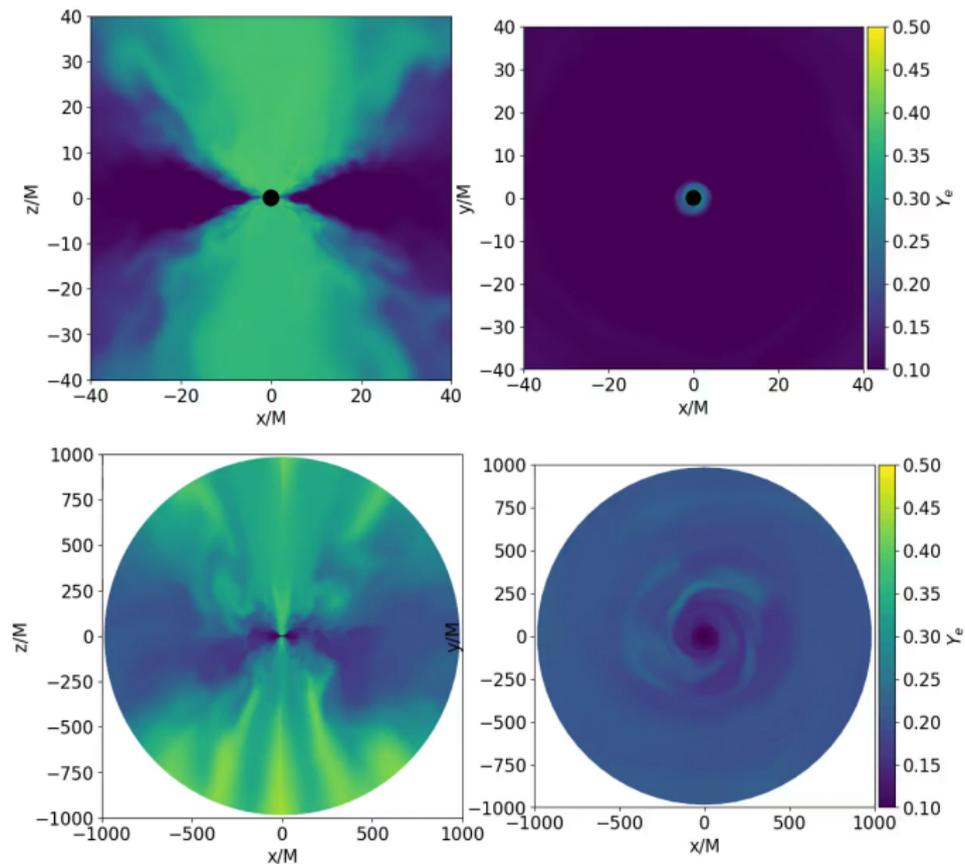
- Neutrino Transport

$$\frac{D}{d\lambda} \left(\frac{h^3 I_{\epsilon,f}}{\epsilon^3} \right) = \left(\frac{h^2 \eta_{\epsilon,f}}{\epsilon^2} \right) - \left(\frac{\epsilon \chi_{\epsilon,f}}{h} \right) \left(\frac{h^3 I_{\epsilon,f}}{\epsilon^3} \right),$$

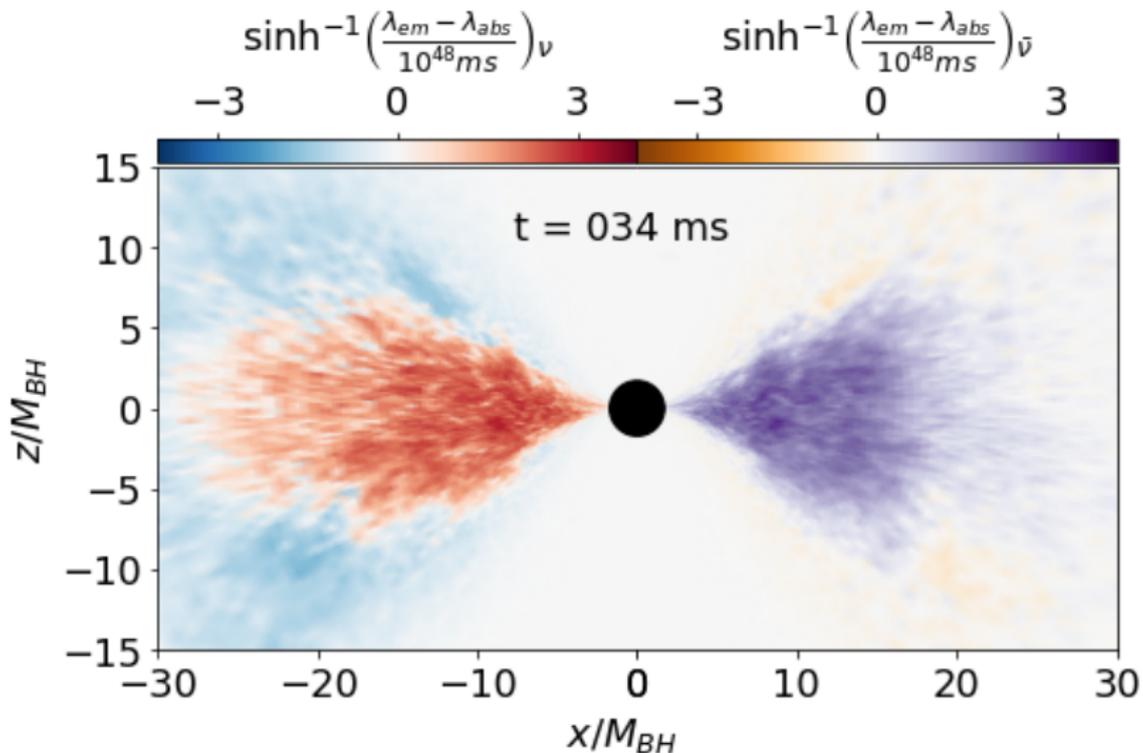
Presenting ν bhlight!

- General relativistic radiation magnetohydrodynamics for kilonova disks
- Open Source! <https://github.com/LANL/nubhlight>
- **Magnetized gas** via *finite volume methods*
 - Standard second-order Gudonov scheme
 - Cell-centered constrained transport for magnetic fields
 - WENO5 reconstruction
 - Local Lax-Friedrichs Riemann solver
- **Neutrinos** via *Monte Carlo methods*
 - Explicit integration along geodesics
 - Probabilistic emissivity, absorption, and scattering
 - Novel biasing scheme ensures all processes well-sampled
- **Coupled** via *operator splitting*
- Built on top of HARM, grmonty, and bhlight.

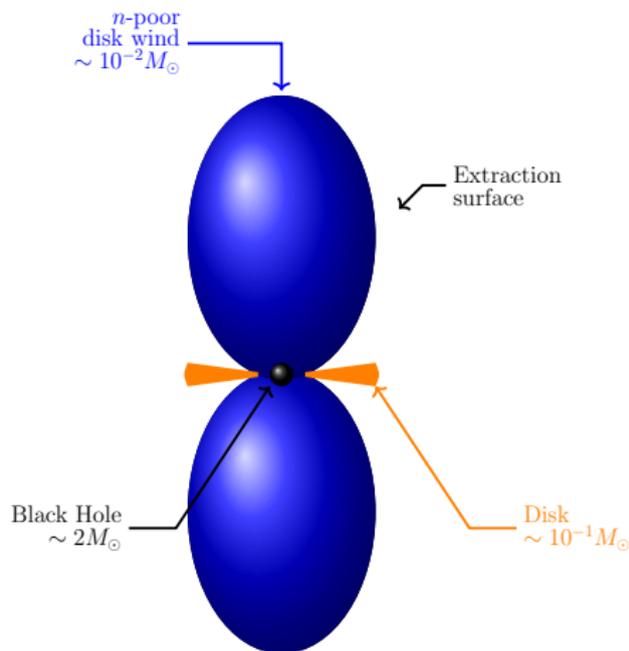
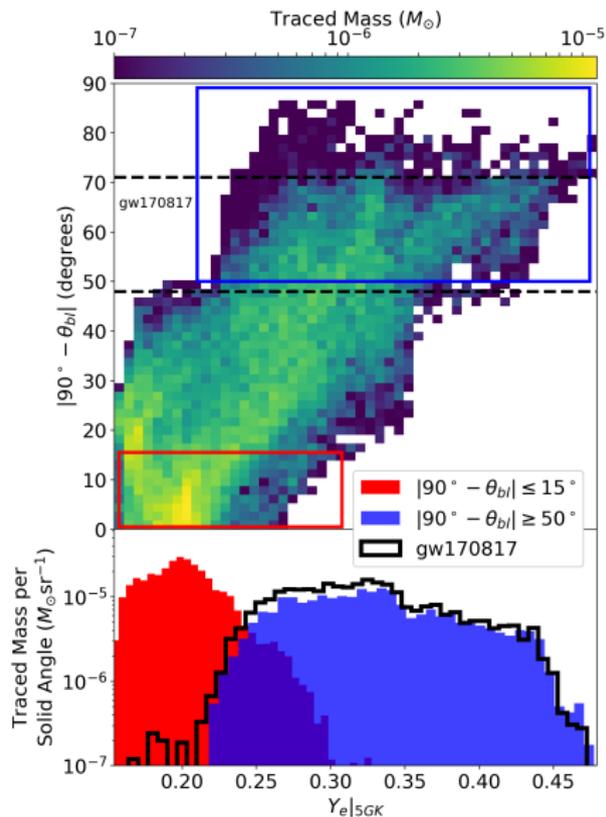
The August 2017 Disk



Neutrino Transport in the Disk

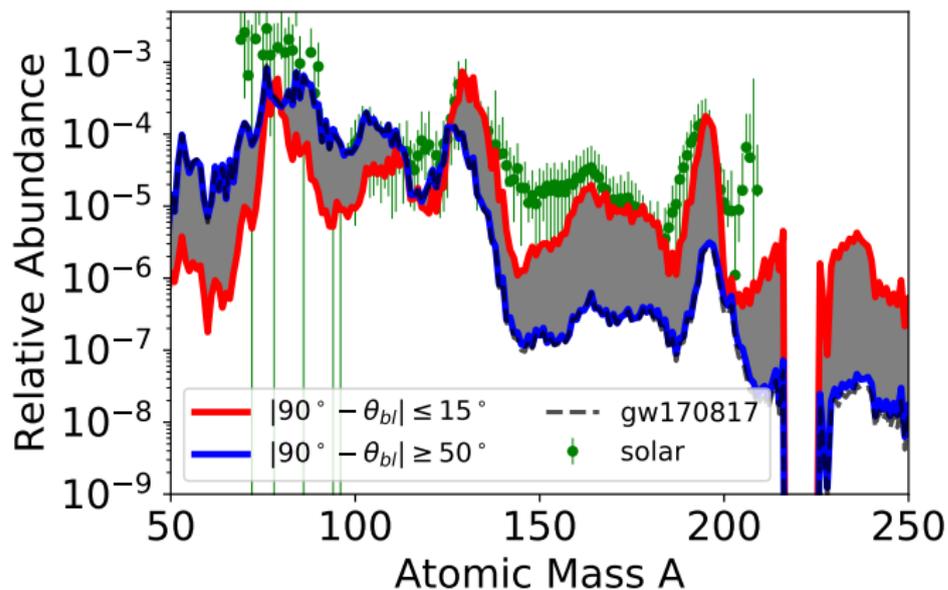


Electron Fraction of the Outflow



JMM et al. PRD 100 023008 (2019)

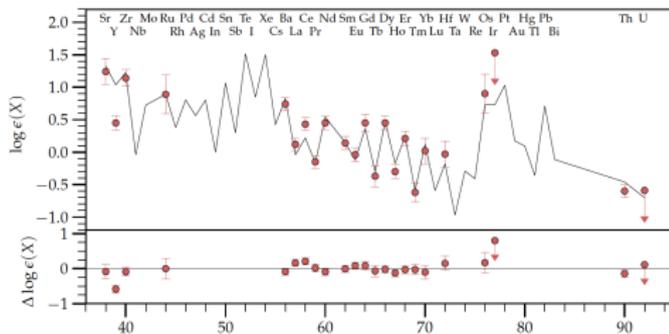
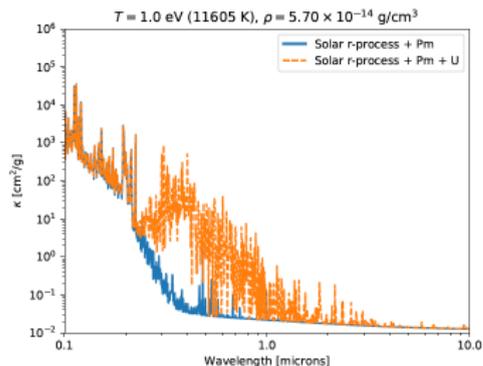
Nucleosynthesis



- r-process networks:
 - SkyNet
 - PRISM
 - CFNET
 - etc.

JMM et al. PRD **100** 023008 (2019)

Nucleosynthesis Feeds Directly into Observables

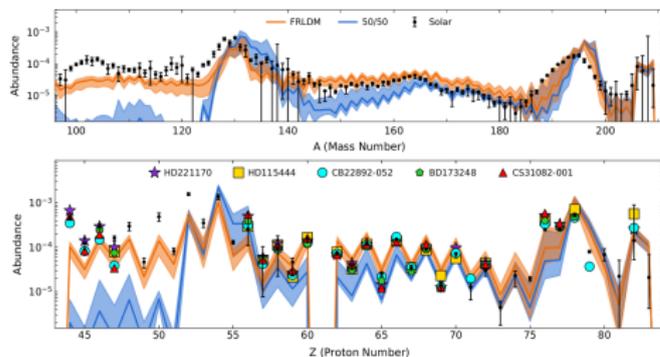


Cain et al. ApJ **898** 40 (2020)

Even,...,JMM, et al. ApJ **899** 24 (2020)

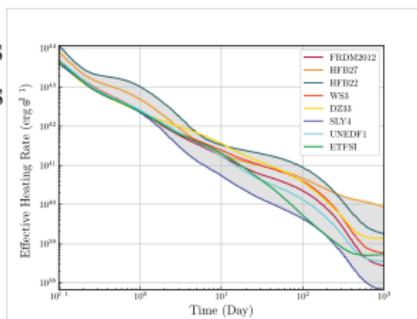
A Sampling of Recent Progress (Not my work)

Fission Yields



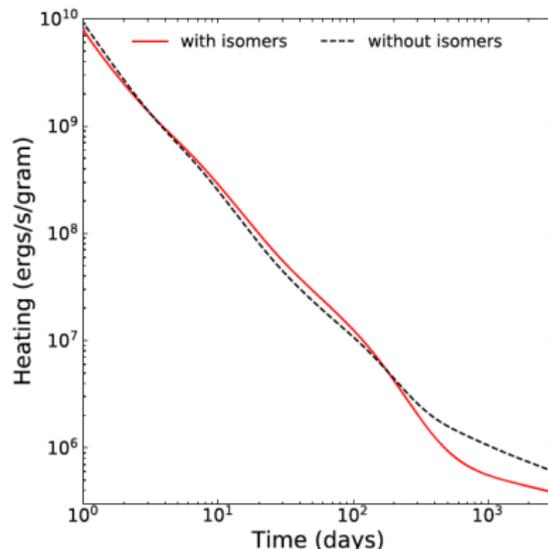
Vassh et al., ApJ **896** 28 (2020)

Heating rates
+ mass models

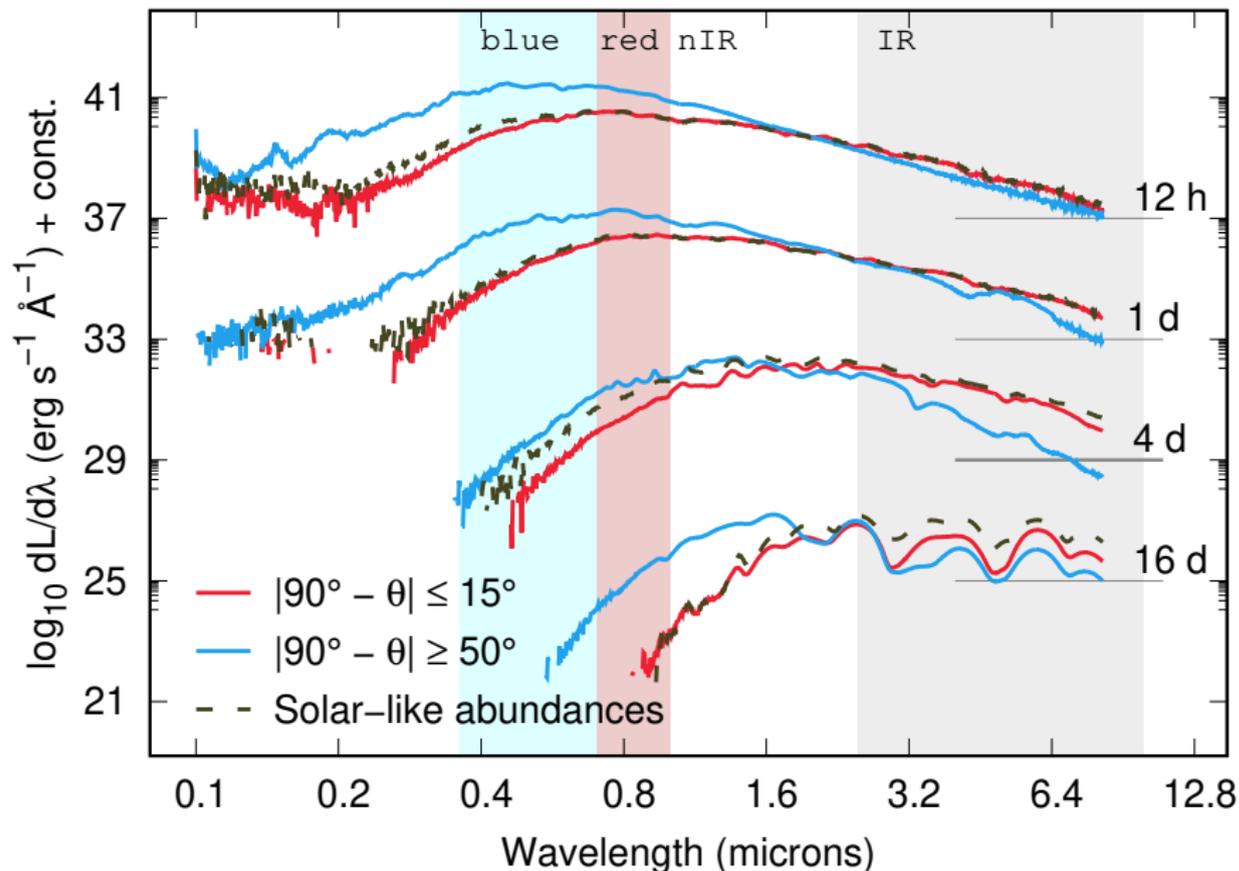


Zhu et al., ApJ **906** 94, (2021)

Astromers

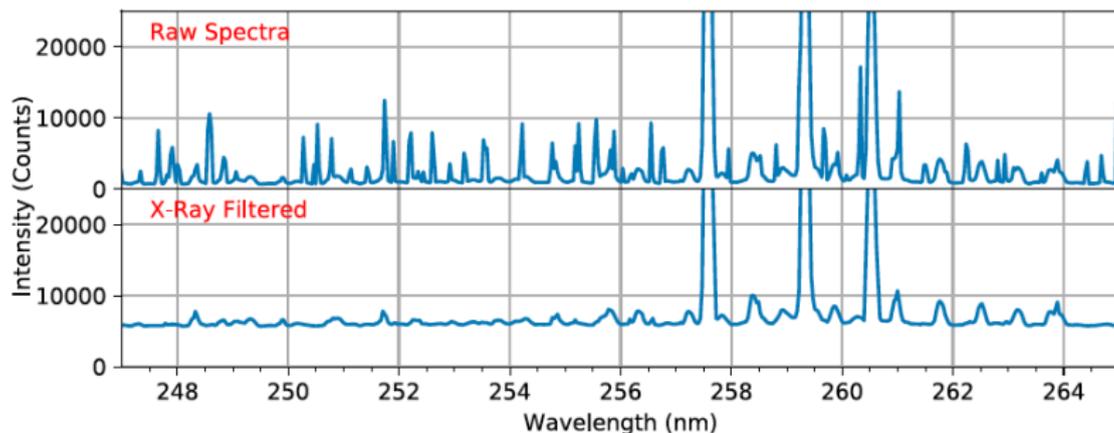


Misch et al., ApJL **913** L2, (2021)



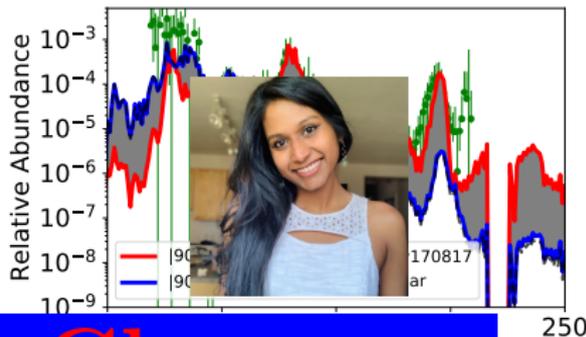
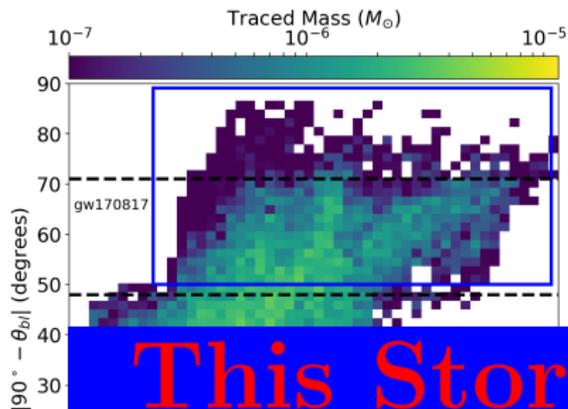
How Opacities are Computed (Not my work)

- Atomic lines determine spectrum
- Lines determined by energy levels, wavefunction, matrix elements
- Usually modeled assuming LTE
 - LANL atomic modeling codes: Fontes et al., JPB **48** 144014, (2015)
 - LANL LTE opacities: Fontes et al., MNRAS **493** 4143 (2020)
 - Lanthanide opacities available at <https://nlte.nist.gov/OPAC>
- Experimental atomic data badly needed

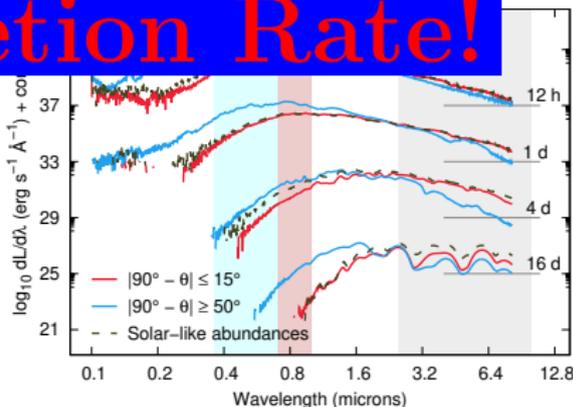
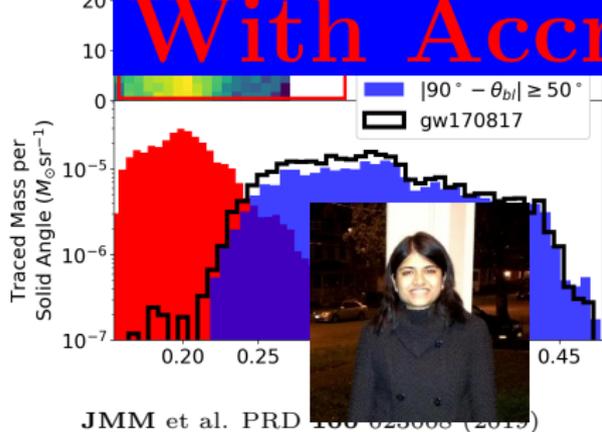


Bromley et al., ApJS **250** 19, (2020).

Outflows, Nucleosynthesis, Observables



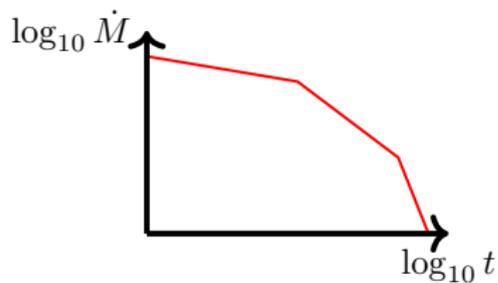
This Story Changes With Accretion Rate!



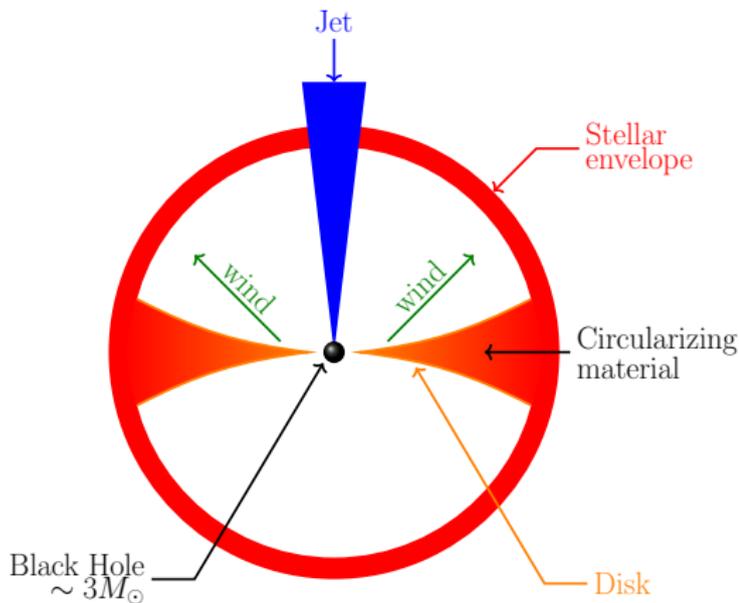
JMM et al. PRD 100 025008 (2019)

What is a collapsar?

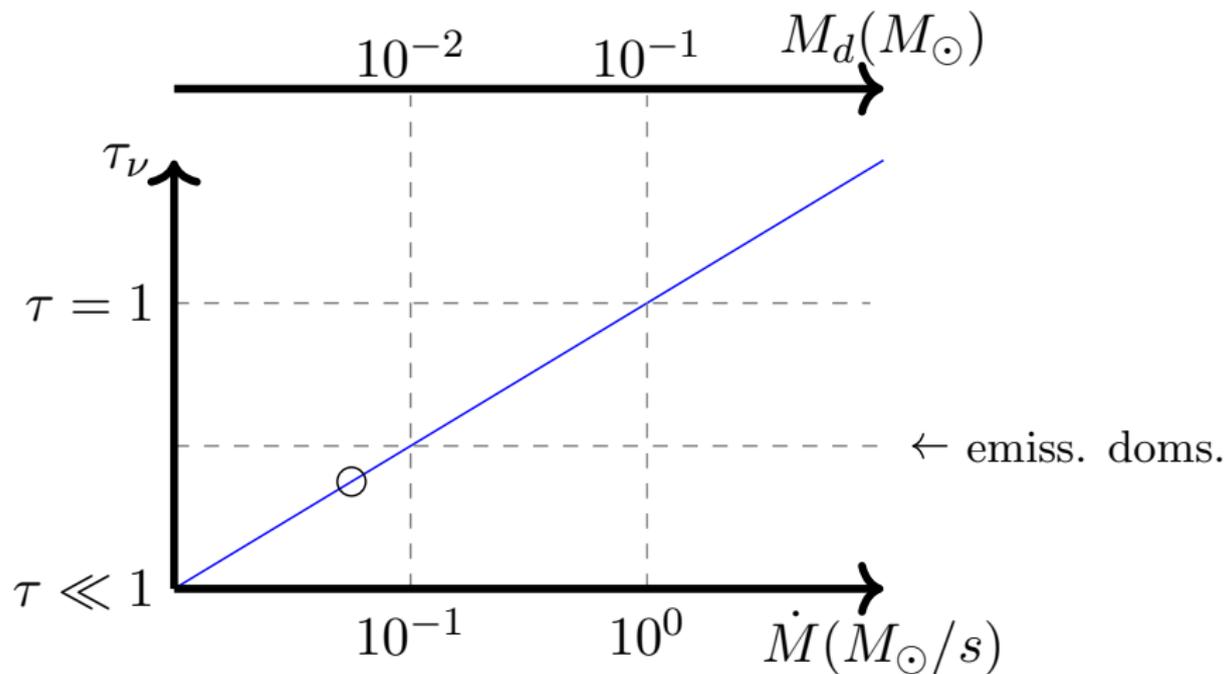
- Accretion times $t \sim 10s$
- \dot{M} between
 - $10^{-4} M_{\odot}/s$
 - $10^{-1} M_{\odot}/s$
- $\rho \sim 10^{10} \text{ g/cm}^3$



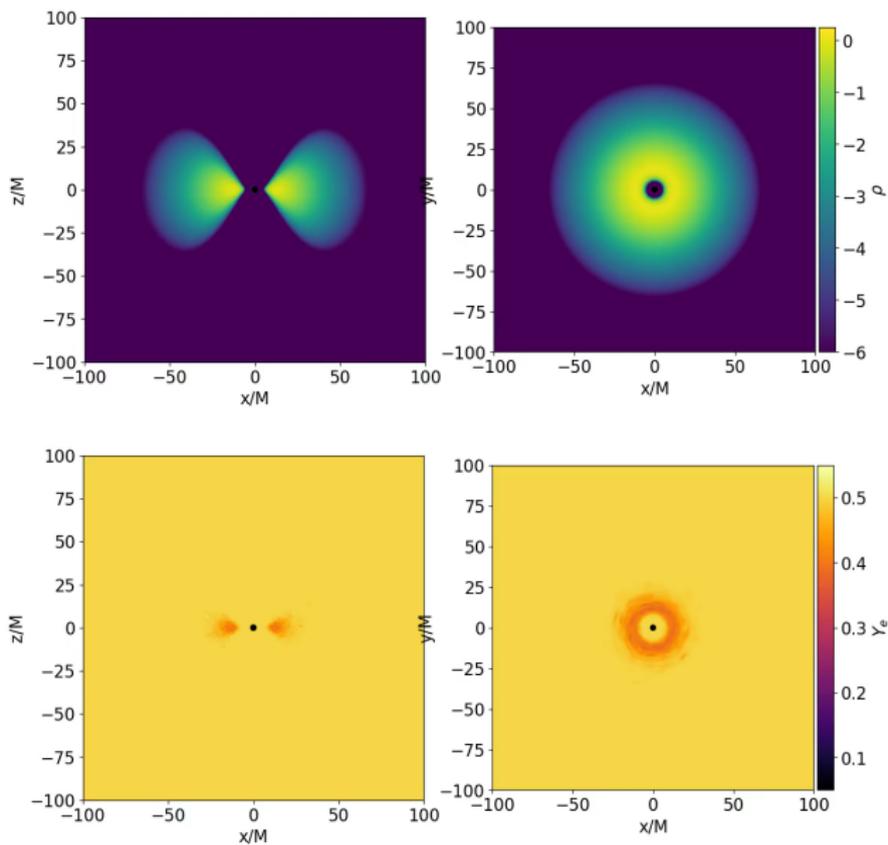
Siegel, Barnes, Metzger. *Nature* **241** (2019)



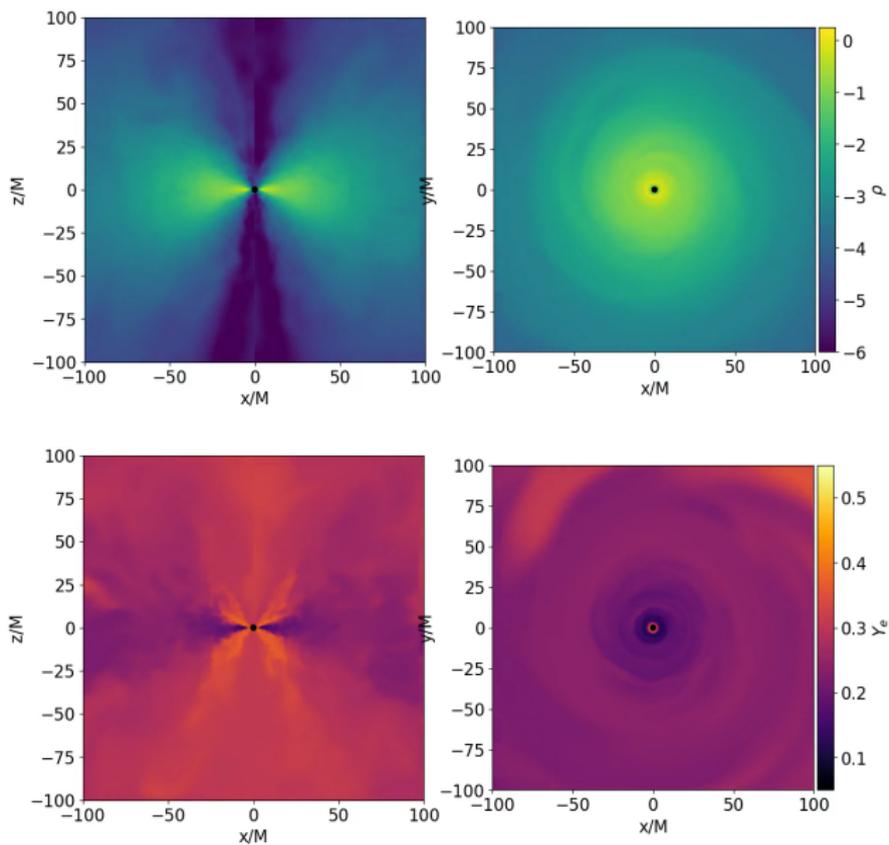
Digging a Little Deeper with a Collapsar Disk



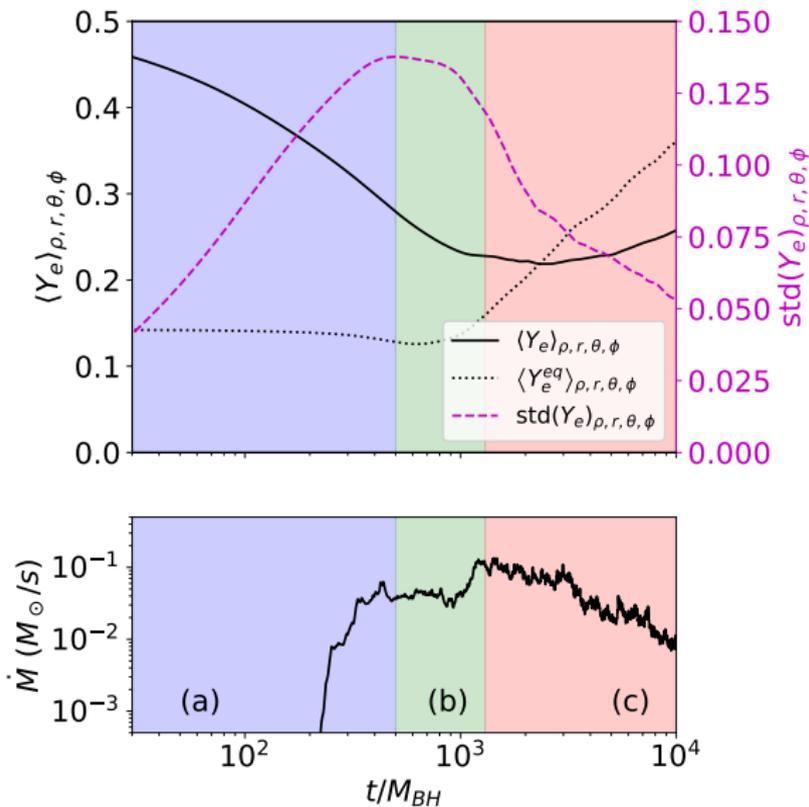
Building a Collapsar Disk



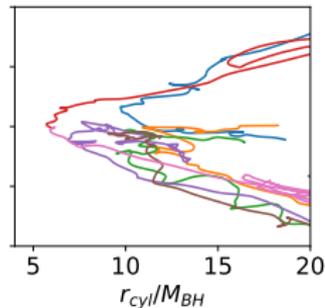
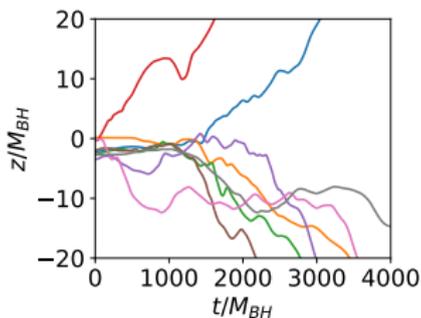
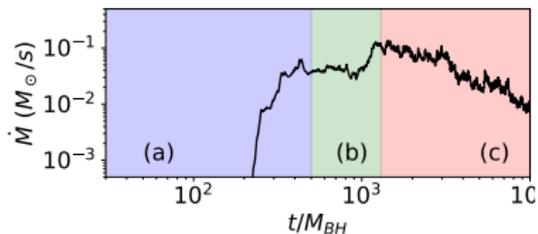
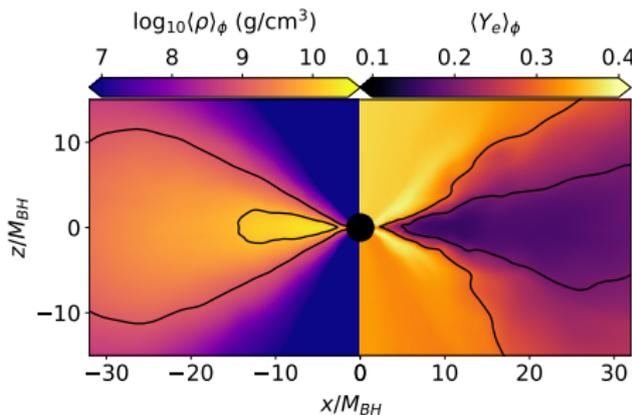
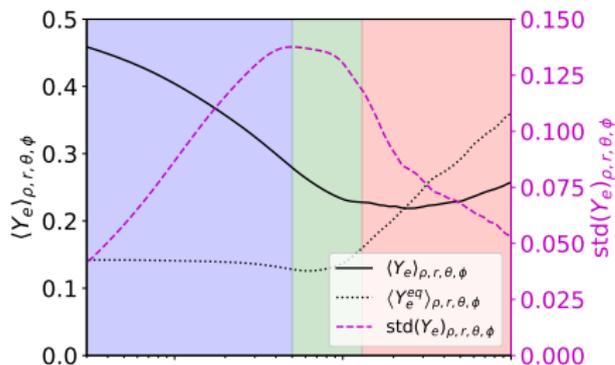
Building a Collapsar Disk



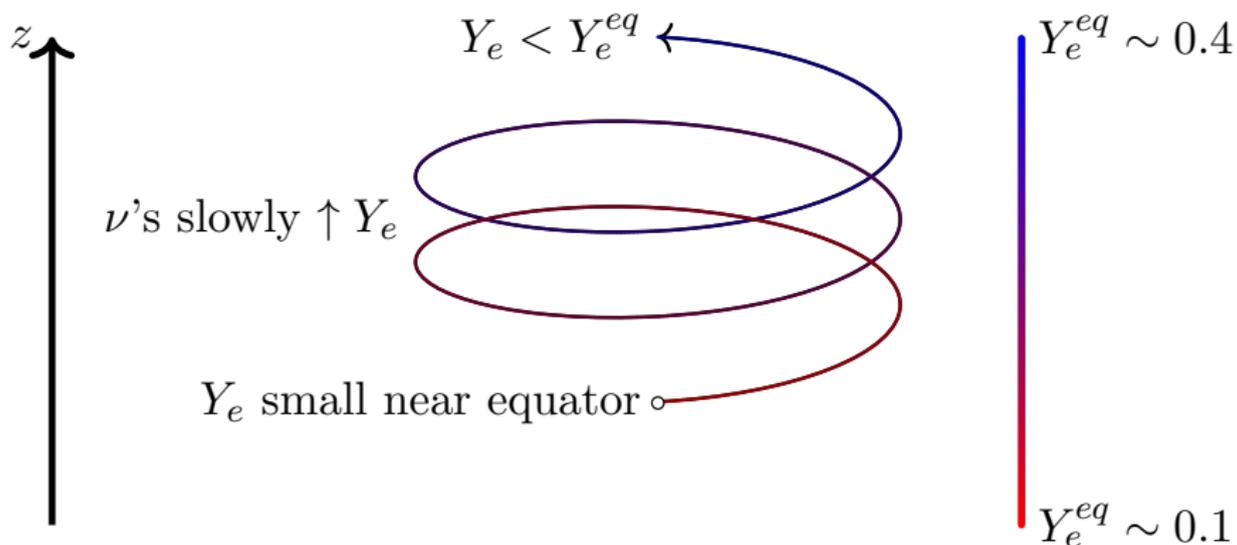
Stationary Disk, No Ye equilibrium!



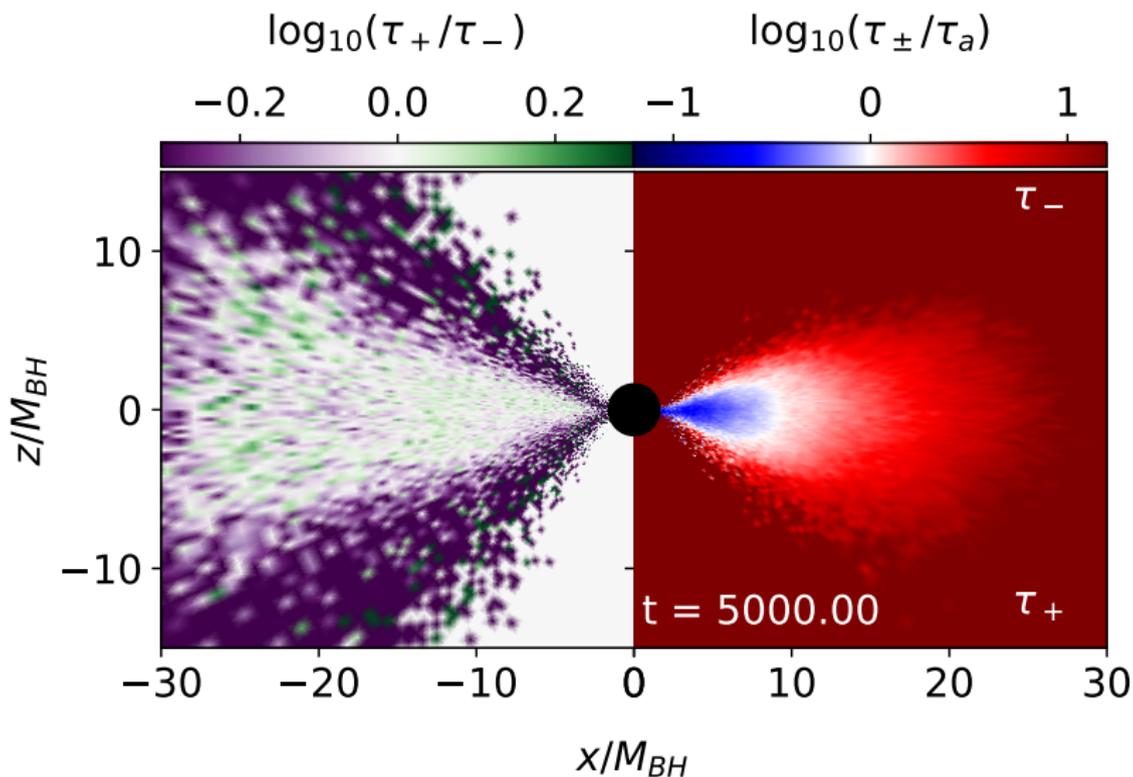
Stationary Disk, No Ye equilibrium!



Miller et al., ApJ **902**, 66 (2020)



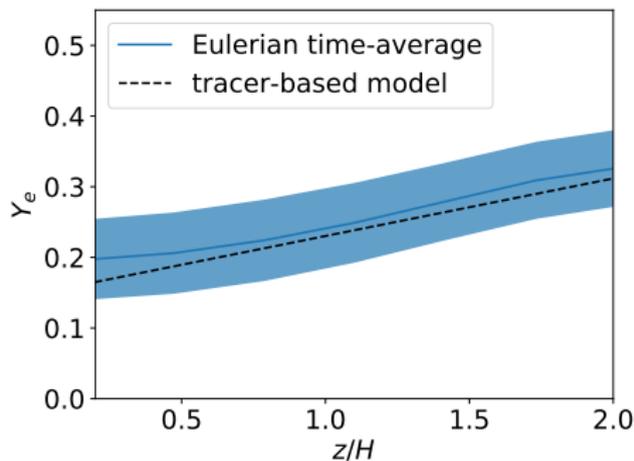
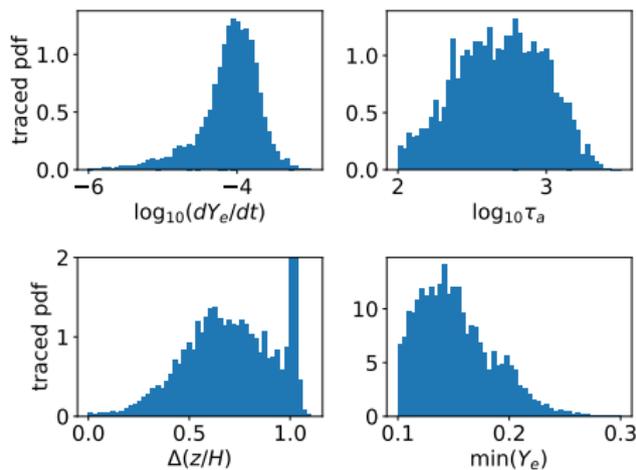
Y_e is set by the balance of Turbulence and Neutrinos!



Miller et al., ApJ **902**, 66 (2020)

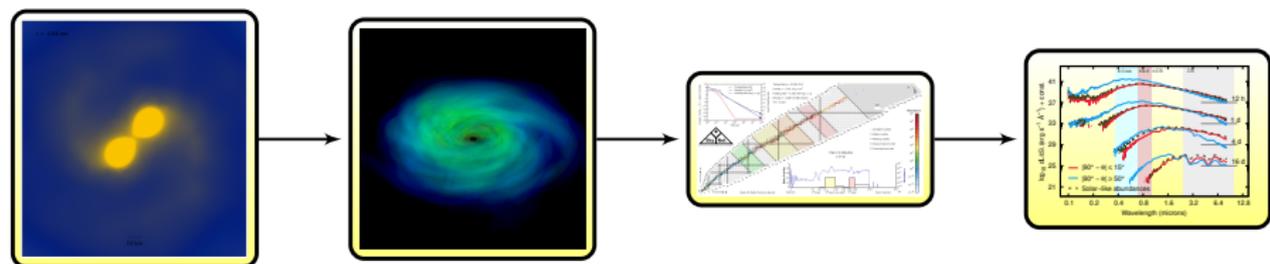
Y_e is set by the balance of Turbulence and Neutrinos!

$$Y_e(z/H) = \langle \min(Y_e) \rangle_{\text{trc}} + \left\langle \frac{dY_e}{dt} \right\rangle_{t,\text{trc}} \left(H \left\langle \frac{dz}{dt} \right\rangle_{t,\text{trc}}^{-1} \right) \left(\frac{z}{H} - \langle \min(z/H) \rangle_{\text{trc}} \right)$$



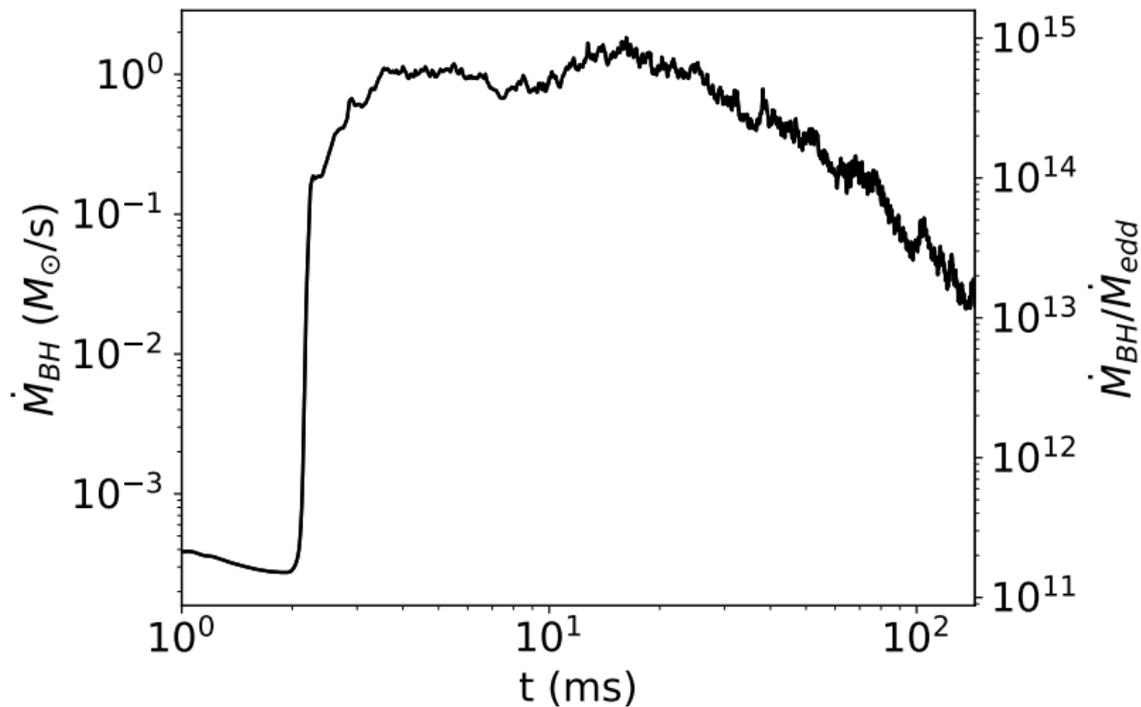
Miller et al., ApJ **902**, 66 (2020)

Take-home Messages

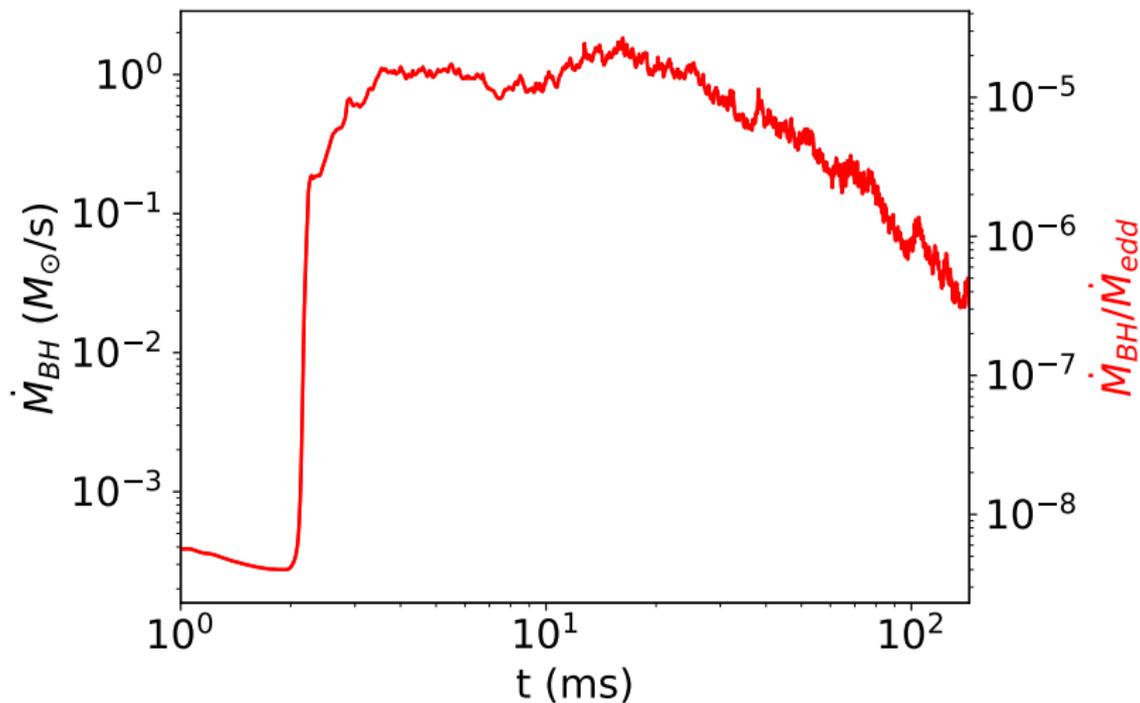


- Neutron star mergers are awesome!
 - Source of GRBs, heavy elements, kilonova afterglow, gravitational waves
- Despite huge successes so far, connecting an observation to an astrophysical system is complicated and challenging:
 - Involves **all four fundamental forces**, many different physical processes, modeled by very different codes/capabilities
 - Many **degeneracies** between astrophysical uncertainty, microphysical uncertainty, etc.
- Neutrino transport essential to get right in the disk. Many open questions remain.

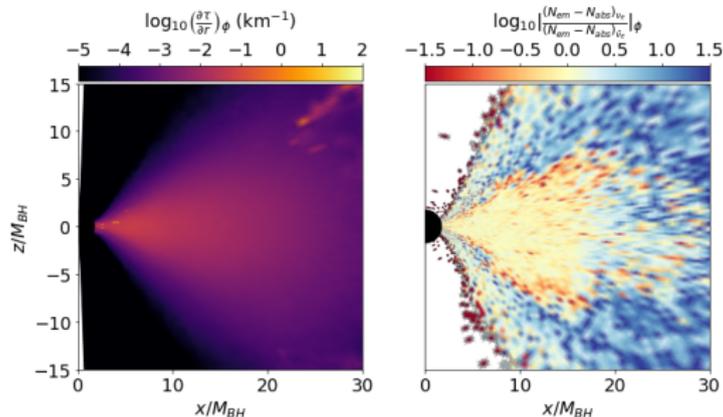
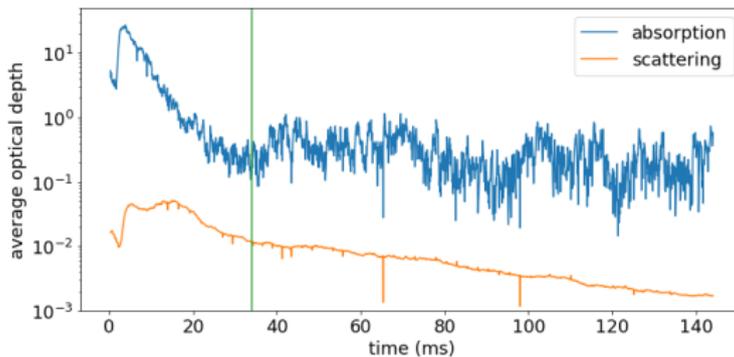
Accretion Rates

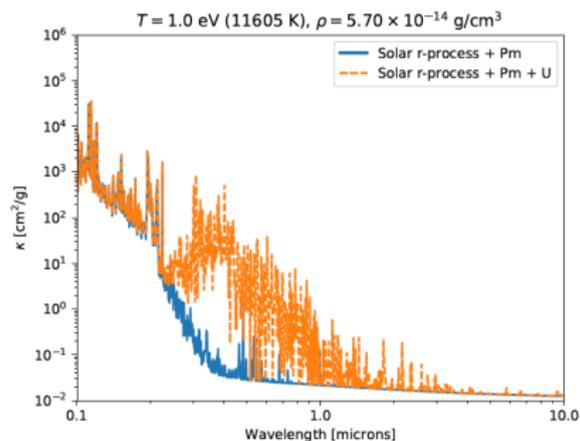


Accretion Rates



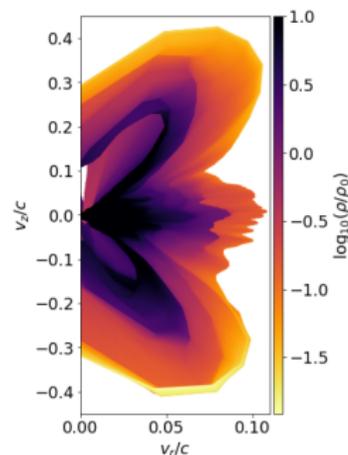
Neutrino Transport





- Not all opacities known, so surrogates often used. Some elements matter more than others.

arXiv:1904.13298



- Geometric effects can be significant, are difficult to treat, and are degenerate with other parameters, such as ejecta mass.

arXiv:204.00102

- Large optical depths, such as inside a neutron star present issues for Monte Carlo
- Need a method that can span the range of optical depths and solve the full transport equation

